WIND CONTROL SIMULATION OF STADIUM 
BASED ON MORPHOLOGICAL ANALYSIS 

Liu Deming¹, Lu Yang¹, Yu Ge¹ 
¹Harbin Institute of Technology, Harbin, China

ABSTRACT
A real stadium case (Harbin International Exhibition 
and Sports Centre Stadium) was taken as simulation 
object in this paper. The sensitivity and associativity 
of chosen simulation platform for 3D models were 
identified at first. Then 28 3D models of stadium for 
CFD simulations, which were all under a certain 
wind environment, were established. These models 
were abstracted out from the morphological varieties 
of stadiums, including the level defences of field area 
with surrounding site ground, the form of canopy, the 
sitting arrangement. Based on simulation results of 
wind contours, comparing, analysis effects of major 
morphological factors on wind environment  of 
stadium field were identified.

INTRODUCTION
More and more iconic stadiums have been built to 
host sport events and serve as landmark around the 
world. Nevertheless, many competitive sport events 
held in stadium are sensitive to wind environment 
because of its open-air feature. For example, 
Sprint and long jump are sensitive to wind speed on 
the tracks and field. Wind speed should be controlled 
under 2m/s for 100m or 200m sprint race according 
to rules, which is sometimes hard to reach in a poorly 
situated and unsuitably designed stadium. An 
achievement which breaks world records might not 
be admitted just because of the over speed of wind on 
field. However, in the open area and under a certain 
environment condition, the wind behaviour in 
stadium is closely related to the morphology of the 
stadium.

Currently, there are 3 major methods to study wind 
environment, including detecting about a built up 
stadium on site, wind tunnel testing of a physical 
model, and digital model simulation. The digital 
simulation is developed on the base of the former 2 
methods, and getting more and more widely used. It 
makes evaluation of environment in the stage of 
design much more convenient, and helpful for good 
resolutions from the very beginning of architecture 
design. But most CFD simulations of stadiums have 
concentrated more on structure safety and equipment 
in the existing research, while much less on 
arhitectural design.

The existing researches on stadiums have constructed 
an instructive foundation. J. Persoon, T. van Hooff 
proposed a simplify way to abstract the figure of the 
spectator stand. Kolovandin, B. A., Valutin, I. A. has 
provided a fine platform for CFD simulation by 
listing the advantages of the model of k-ε. T.van 
Hooff, B.Blocken, M.van Harten assembled 12 
different generic stadium configurations which 
almost have covered most existing and mainly kinds 
of stadium, getting CFD simulations of wind flow 
and WDR (wind-driven rain). Gu Lei, Qi Hongtu 
took the Olympic Tennis Center as object, simulating 
the wind pressure on shelter and getting the wind 
speed distribution of inside field in order to 
determine which form of shelter is better to weaken 
the influence of the wind. Yu Fengquan made two 
pairs of simulations of the Weifang Olympic Center 
Stadium containing variables on different shelter 
slope and switched access tunnel, getting the best 
typology for only this field.

To sum up, the research documents on wind control 
of stadium has provided a comprehensive basement 
for simulation, but few focused on the competition 
field, especially for the sprint race area. They always 
get some factors that may influence the field’s wind 
condition and speculate ways to improve it by 
concerning one object with few transformer or only a 
single configuration, which has not fully covered 
most types of stadium. However, the various 
combination form of the canopy and the sitting 
arrangement impact much on the field, and also the 
level defereces between the sport field and 
sourrounding site ground, which has not been 
systemical considered. It should be tested by the 
means of CFD simulation in order to get which forms 
are better for the wind speed control.

In this paper the Harbin International Exhibition and 
Sports Center Stadium was taken as observed object, 
8 digital 3D models concerning on the varieties of 
level of field area, and 20 others on the various 
configuration of canopy and the sitting arrangement. 
All groups of models are under the same wind 
environment, in which only one variable is controlled 
at one time, including the speed and direction of the 
wind, the height and the density of surroundings. The 
date of the surrounding environment is proposed to 
fit the simulation best based on both the field survey 
and the local annual records.
And the surrounding wind speed is 10m/s at the height of 10m (the actual wind speed measured at the field), the direction is south to west 15° (local predominant wind direction), and the height and the density of surrounding buildings is taken as 0 and 0.5. The governing equation of this experimental prototype is Navier-Stokes, and the viscous model is k-ε. Then identify the simulation platform made for the 3D models is sensitive and associative using the mathematical and physical model raised above to make sure the accuracy of the whole simulation. Taking the wind speed distribution of the height of 1.22m, which is the height of the anemoscope testing at the contest, compare the speed and the distribution of the wind to judge the wind environment under various situations. In addition, the existing of the spectators will complicate the research because of the diversification of the amount and location, so this paper only concerns on the situation without spectators.

This paper contains 5 sections. Section 2 presents the condition and boundary of the stadium, and the form of the 28 models. Section 3 contains the identifying of the platform. After confirming the platform is sensitive, section 4 takes the simulations and finds out the major construction design factors based on the results. At last, section 6 concludes the whole passage.

DESCRIPTION AND COMPUTATION OF THE TYPICAL STADIUM MODEL

Description of the stadium configurations

Harbin International Exhibition and Sports Centre Stadium is capable of holding 50,000 spectators watching the game at the same time. Its form is combined of bilateral canopy and enclosed stand, and the circle of below stand sinks half into the ground. It’s exterior dimensions are 247.5m wide, 261.7m long, and 53.5m high (Figure 1b). The span of the canopy is 247.5m with height of 48.4m, downward-sloped in 25° (Figure 1c, 1d). The stand is 21.7m above the ground and 11m below the ground.

<table>
<thead>
<tr>
<th>Table 1: Models on level defences</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SINKING OF THE CIRCLE</strong></td>
</tr>
<tr>
<td>Z-0</td>
</tr>
<tr>
<td>total 11m</td>
</tr>
<tr>
<td><strong>DISTANCE BETWEEN CANOPY AND STAND</strong></td>
</tr>
<tr>
<td>Z-0</td>
</tr>
<tr>
<td>9m</td>
</tr>
<tr>
<td><strong>CHINKS IN STAND</strong></td>
</tr>
<tr>
<td>Z-0</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td><strong>GATE OF ACCESS TUNNEL</strong></td>
</tr>
<tr>
<td>A-2</td>
</tr>
<tr>
<td>Shut down</td>
</tr>
</tbody>
</table>
Table 2: Models on configuration of canopy and stand (CS presents for circle stand; BS presents for bilateral stand; FS presents for four stands)

<table>
<thead>
<tr>
<th>CIRCLE CANOPY</th>
<th>Upturned</th>
<th>Plane</th>
<th>Dipping</th>
<th>Saddle</th>
</tr>
</thead>
<tbody>
<tr>
<td>C S</td>
<td>a-1</td>
<td>a-2</td>
<td>a-3</td>
<td>a-4</td>
</tr>
<tr>
<td>B S</td>
<td></td>
<td></td>
<td>a-5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BILATERAL CANOPY</th>
<th>Upturned</th>
<th>Plane</th>
<th>Dipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>C S</td>
<td>b-1</td>
<td>b-2</td>
<td>b-3</td>
</tr>
<tr>
<td>B S</td>
<td>b-4</td>
<td>b-5</td>
<td>b-6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SINGLE CANOPY</th>
<th>Upturned</th>
<th>Plane</th>
<th>Dipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>C S</td>
<td>c-1</td>
<td>c-2</td>
<td>c-3</td>
</tr>
<tr>
<td>B S</td>
<td>c-4</td>
<td>c-5</td>
<td>c-6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4 SIDES CANOPY</th>
<th>Upturned</th>
<th>Plane</th>
<th>Dipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>F S</td>
<td>d-1</td>
<td>d-2</td>
<td>d-3</td>
</tr>
</tbody>
</table>

The racing area is made as the IAAF standard.

28 models are made for the demand of the study aiming at different factors. 8 models (Table 1) are directed against the level defences in 4 groups which cover sinking level of the circle (Z-0, A-1, A-2), different distance between the canopy and the stand (Z-0, B-1, B-2, B-3), none sink in the stand (Z-0) compared with 1m-sink in every 5m height in stand (C-1), and the access tunnel open (D-1) or shut (Z-0). 20 models (Table 2) are about the configuration of canopy and stand in 4 groups too. They are grouped according to the forms of different canopy and stand. The canopies cover enclosed ones (abbreviation for EC), bilateral ones (BC), single ones (SC), four sides ones (FC), which have concluded most of the possible existing forms in large athletics stadiums that have the ability to hold international track and field events. Meanwhile the slope angle of the canopy shows upturned, plane and dripping. And the form of the stand contains circled stand (CS), bilateral stands (BS) and 4 stands (FS). But not each kind of canopy and stand can be combined. So 20 groups has been raised above according the statistics and conclusion of the existing typical stadiums.

### Computational model

Set up the surrounding models based on the physical dimension of the stadium mentioned in section 2. The wind outlet frame of the computational domain is chosen at more than 5 times of the size of the stadium itself and behind it. And the height is also overtop t5 times of it. So the surrounding dimension is 2000*1200*250m³ (L*W*H), which can let the wind fully flow.

This space model is vertically divided into three parts: field area, stadium stands and canopy, space above the stadium. And these 3 areas are made grids from dense to sparse to raise the operating speed of the computer effectively with a high quality of grids. The field area’s grid is vertical encrypted hexahedral unstructured grid because of its importance as the observed item, which makes the observation of any section of elevation easier. The stadium construction area is the main object influencing the field’s wind environment, and it’s grid is tetrahedral unstructured grid. The area above the stadium is the auxiliary area for the fully flow of the wind, so its grid is sparse hexahedron. The whole amount of grids is 970,000.

The grid density is not evenly arranged in each model, but gradually increased in three gradients from space above the field to the field, which reaches the maximum in area close to the field. Thus, accuracy of results is insured while the computational operation time is decreased efficiently.

The solver used in this simulation is separate solver in FLUENT 6.3.26, which meets the requirement of the research, and can save more time and computer memory in reasonable range. This experiment takes the viscous incompressible Navier-Stokes equation as the governing equation, k-ε model as the turbulence model, in which k refers to the kinetic energy of the turbulent fluctuation while ε refers to its dissipation rate. This model has wide applicability, efficiency and reasonable accuracy, which has made it a main tool in engineering flow field calculation. The control equations are as below:

**Continuity equation:**

\[
\frac{\partial \rho u}{\partial x} = 0
\]  

(1)

**Momentum equation:**

\[
\frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_i} \left( \rho u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_j} \right] + \rho (T - T_w) g_i,
\]  

(2)
Turbulent kinetic energy equation (k equation):
\[
\frac{\partial k}{\partial t} + \nabla \cdot (k \mathbf{u}) = \nabla \cdot \left( \frac{k}{\sigma_k} \nabla \sqrt{\frac{k}{\rho}} \right) + \left( \frac{3 \varepsilon}{k} \right) \rho_0
\]
(3)

Turbulent energy dissipation rate equation (ε equation):
\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \mathbf{u}) = \nabla \cdot \left( \frac{\varepsilon}{\sigma_\varepsilon} \nabla \sqrt{\frac{k}{\rho}} \right) + \frac{\varepsilon}{k} \left( \nabla \cdot \mathbf{u} \right)^2 - \frac{\varepsilon}{k} \nabla \cdot \left( \frac{k}{\sigma_k} \nabla \sqrt{\frac{k}{\rho}} \right)
\]
(4)

The empirical constant is according to the propose of D. B. Spalding and B. E. Launder (Table 3).

Table 3: Empirical constant in k-ε model

<table>
<thead>
<tr>
<th>CM</th>
<th>C1</th>
<th>C2</th>
<th>ΣK</th>
<th>ΣE</th>
<th>ΣT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1.3</td>
<td>1.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

This model takes the height of 10m as the wind intake height, and the air inlet as the velocity inlet boundary. The initial speed is taken as 10m/s according to the actual measurement listed in Table 4. The wind direction in this simulation is also from the actual wind as west by south 15°, showing as the direction of “-Y”. The air outlet is free flow boundary with no reflected pressure or other influences to the upstream wind field. Meanwhile, the wall and ground of the stadium construction is regarded as solid with no relative motion. The reference pressure is standard atmosphere. This research takes no surrounding buildings in account, because most of them are at the areas influenced by upstream wind and far away from this stadium, which also makes the control of the facor of constructing itself easier. So all simulations take same the height and the density of surroundings as 0 and 0.5, and the ground is uniform sand surface.

The survey of the acutl stadium was held at 12:00-13:00p.m., 14th April, 2014, when the wind speed at that time is stabilize. Local observatory issued a large wind warning at 10:10 a.m. in that day: the wind speed of most of the city is 5-6 grade (equals to 8.0-13.8m/s), the gust might even reach 7grade (equals to 13.9-17.1m/s). 6 observation points are chosen at the height of 1.22m (Figure 2). The wind speed of Point 1 at the extension line of the stadium’s short axis is taken as the inlet boundary condition. Point 2-6’s data is used to identify the sensitivity of simulation platform. Point 2, 3 are on the extension line of the long axis at the 2nd layer outdoor platform because of the 3.6m dispersion of the short axis. Point 4, 5 lay on the beginning line and the finishing line while point 6 lays on the centre point of the filed, which three is chosen to validate the simulation results. Record the instant wind speed with a camera for 5 minutes, and then pick out the maximum data to get the average speed of the observation point (Table 4). In addition, the recorded wind direction of point 1 is west by south 15°, which is taken as the initial wind direction of all simulation.

Table 4: The actual measured maximum speed of each minutes and average speed of the observation point (m/s)

<table>
<thead>
<tr>
<th>MIN</th>
<th>0-1</th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.20</td>
<td>7.75</td>
<td>9.9</td>
<td>11.4</td>
<td>11.15</td>
<td>9.48</td>
</tr>
<tr>
<td>2</td>
<td>3.18</td>
<td>4.60</td>
<td>4.35</td>
<td>3.85</td>
<td>4.65</td>
<td>4.13</td>
</tr>
<tr>
<td>3</td>
<td>3.38</td>
<td>4.4</td>
<td>6.63</td>
<td>5.93</td>
<td>5.75</td>
<td>5.22</td>
</tr>
<tr>
<td>4</td>
<td>1.58</td>
<td>1.70</td>
<td>2.43</td>
<td>1.93</td>
<td>2.00</td>
<td>1.93</td>
</tr>
<tr>
<td>5</td>
<td>1.90</td>
<td>1.85</td>
<td>2.00</td>
<td>2.23</td>
<td>2.28</td>
<td>2.05</td>
</tr>
<tr>
<td>6</td>
<td>2.93</td>
<td>2.98</td>
<td>2.58</td>
<td>3.43</td>
<td>3.86</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Simulation based on recorded data
The simulation is operated at a diacron 2.0GHzCPU, 2G internal storage computer with 2000 iteration costing 4 hours to get convergence. Then use tecplot360 2013 to get the wind speed distribution of the height of 1.22m (the height of point 4-6), and 13.4m (the height of point 2-3), getting the velocity contour data. And Photoshop the results picture as showed in Figure 3, make the stadium lay direct north to south. The wind direction is west by south 15°. The 100 meter track is at west side, close to the air inlet.

Figure 2: Main observation point

The survey of the actual stadium was held at 12:00-13:00p.m., 14th April, 2014, when the wind speed at that time is stabilize. Local observatory issued a
Table 5: Simulated wind speed range of observation point (m/s)

<table>
<thead>
<tr>
<th>POINT</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEED</td>
<td>&gt;4</td>
<td>4-6</td>
<td>1-2</td>
<td>1-2</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Table 6: Measured wind speed of observation point (m/s)

<table>
<thead>
<tr>
<th>POINT</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEED</td>
<td>4.13</td>
<td>5.22</td>
<td>1.93</td>
<td>2.05</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Figure 4: Speed isograms of 8 groups concerning on level defences

Figure 5: Speed isograms of 20 groups concerning on the associated form of canopy and stand
Comparison

The comparison of the Table 5 and Table 6 shows that the actual speed data match the simulated speed data well under the error range. So the chosen platform, equation and technological process fit the requirement this paper need, which make sure of the accuracy of the following simulations. The main purpose of the study is to find out the aspects of the form of stadium to which wind environment of stadium field is sensitive, provided for attention of...
architectural design. Thus, simulation experiment design has focused on relative comparison of combination of various shape forms, and the accuracy of each single model data is temporarily not the main goal. Therefore, this grid density setting can meet the requirements.

RESULTS

Results of the level deference of field area with surrounding site ground

The speed isograms concerning on level of defences is showed in Figure 4. This section discusses the result in 4 aspects: sinking of the circle (Z-0, A-1, A-2); the distance of canopy and stand (Z-0, B-1, B-2 B-3); existing of the chink of the stand (Z-0, C-1); the open of access tunnel gate (A-2, D-1).

- **Comparison between Z-0, A-1 and A-2**: The wind speed of the stadium field is the minimum and most uniform distribution in Z-0. Z-0 also has the best situation in 200m racing track. Only little north part of football area exists excessive wind speed (more than 2m/s). On the contrary, A-1’s situation presents worst. The average wind speed reaches the maximum.

So, making the circle part if the below stand fully sink can develop the field’s wind environment effectively. And only sinking parts of it should be avoided.

- **Comparison between Z-0, B-1, B-2 and B-3**: As the distance of canopy and stand changing from 9m to 3m, the quality of the field’s wind environment decreases first and the increases. When the distance becomes zero, it turns into the worst condition.

So, each type of stadium should have a most appropriate distance between canopy and stand, which can be tested before design, and should avoid no distance.

- **Comparison between Z-0 and C-1**: When the chink increases, the excessive speed area raises too, moving towards to the center, which makes wind speed on football field area unsuitable for football match.

So, whether to set this chink or not depends on what kind of contest the stadium meanly hold: if football match is more usually held, set no chink; on the other side, existing chink fits the sprint match well.

- **Comparison between A-2, D-1**: The open of the access tunnel influence the field’s wind environment a lot, especially the area near the tunnel where the speed raising clearly and changes sharply. It makes the wind unsuitable for the sprint.

So, the gate on tunnel shuold be shut down at the time when sprint is held to make the wind environment better.

Results of the associated form of canopy and stands

The speed isograms concerning on associated form of canopy and stand is showed in Figure 5, analysed and summarised in Figure 6, which covers the entire filed and 100 meter track. To make the comparison comprehensive, this section discusses the result in 5 groups divided by the style of canopy. And first compare various form of stand under certain canopy in each group, and then explore the influence of different canopy over the same stand.

- **Group A**: When the canopy is circle but not saddle type (a-1, a-2, a-3), a-3 appears the best situation for the slow wind speed and uniform distribution. As the angle of the canopy raises to a-2 or a-1, the area of over-3m/s-speed increases and the distribution varies sharply, particularly for the a-1 whose 40 percent of its field’s speed is over 4m/s. Moreover, when the canopy is circle and saddle type (a-4, a-5), the wind environment presents best, especially for the a-5.

- **Group B**: No matter the stand is enclosed or bilateral under the bilateral canopy, the plane angle of canopy (b-2/b-5) is the worst type for the wind environment. On the contrary, the upturned ones fit best (b-1/b-4). And when the angle of canopy is certain, bilateral stand is better than circle ones. For example, compared to b-1, the area of excessive wind speed in b-4 turns towards west and decreases, which has developed the quality of football field.

- **Group C**: When compare between the same types of stands under single canopy, the upturned canopy (c-1/c-4) is the best. And the plane type is the worst because of its influence make 90 percent of the field’s wind speed excessive. When compare between bilateral stand and enclosed ones under same angle of canopy, the former ones wins. For example, the over-speed wind area covers more in c-1 than in c-4. In addition, c-4 presents to be the best in-group C.

- **Group D**: When the canopy is 4 sides type, the stand usually present in 4 parts too. As the angle of canopy change from upturned (d-1) through flat (d-2) to dipping (d-3) finally, the wind environment developed gently. Especially in d-3, it has least area of over-3m/s-speed, and uniform most distribution. But it also brings little fast speed wind to the 200m tracks.
• Compare all groups: If use the symbol “>” as the meaning of bring better wind environment of field, when the angle of canopy is upturned, 4 sides canopy > single canopy > bilateral canopy > circel canopy. When the angle of canopy is flat, 4 sides canopy > circel canopy > single canopy > bilateral canopy. When the angle of canopy is dipping, 4 sides canopy > circle canopy > single canopy > bilateral canopy. And circle saddle type of canopy is the best one compared with all other groups.

In summary, as the angle of, the enclosed canopy (not saddle one) and four sides ones changing from upturned to plane then to dipping, the wind environment in field decomposes. And the circled saddle ones always presented best with any other kinds of stands. When the canopy appear as bilateral ones or single ones, bilateral stand is better than enclosed stand, and the upturned angle is better than dipping while the worst is plane type. Overall, the enclosed saddle canopy with bilateral stand is the wisest choice, and the four sides canopy with stand follows.

CONCLUSION

This paper use CFD simulation exploring the factors of stadium construction which influence the field’s wind environment based on the former researches. It first sets up and confirms the platform to make the whole simulation effective. And then abstract the probably existing 28 types concerning on level defences and associated form of canopy and stand into models and do the simulation. At last, it proposes the following conclusion based on the result of speed isoelms.

The influence of the factors simulated in this paper is huge and sensitive to the field’s wind environment. The factors cover the level defences like the sinking of the circle, distance between canopy and stand, existing of the chink of the stand, the open of access tunnel. And also conclude the associated forms of canopy and stand. Depending on the simulation it gets the best situation under each factor’s influence. Since simulation experiment, design has focused on relative comparison of combination of various shape forms, the accuracy of each single model data needs refining in further studies.

• If the level defences allow the circle sink totally, then sink it, and avoiding partly sunk.
• The distance of canopy and stand exists a best answer, which need to be tested using simulations. But it should avoid none distance.
• The existing of the chink of the stand itself depends on the mainly held competition type.

• The access tunnel should be shut down when the sprint is held, which can avoid the high speed of wind around the track.

• Refer to the associated form of canopy and stand, enclosed saddle canopy with enclosed stand or bilateral stand is the best combination. And followed by the four sides canopy. When the canopy is enclosed ones (not saddle) or four sides ones, the dipping angle of the canopy can bring the best wind environment. Meanwhile, if the canopy is bilateral ones or single ones, the angle should be upturned.

REFERENCES


